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HIGH POWER VLF TRANSMITTING ANTENNAS USING FAST WAVE HORIZONTAL DIPOLE ARRAYS

by

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ABSTRACT. Horizontal VLF transmitting dipole arrays are much easier and less expensive to construct than vertical VLF transmitting antennas in use at the present time. The horizontal dipoles have much greater power-radiating capability and bandwidth. The theoretical and experimental effects of mutual resistance on array efficiency gain over one dipole are presented. The radiation efficiency is greatly increased by increasing the wave velocity along the resonant dipole. Radiation characteristics of a theoretical 18-dipole array on Hawaiian lava are shown. The antenna radiation pattern needed at VLF in order to get omnidirectional coverage is presented. Directivity is needed due to the non-reciprocal east-west propagation attenuation.

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FOREWORD

The work described in this report was conducted in the Space Geophysics Division, Research Department, from January 1969 to July 1969 as a part of the VLF Research Program. This portion of the program was funded as an Independent Exploratory Development project.

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NOMENCLATURE

c Free-space wave velocity (3×10^8 meters/sec)

C_p Antenna distributed capacitance to ground (farads/meter)

E_θ Electric field strength in elevation plane

E_Z Electric field strength in azimuth plane

F Isotropic array factor

I_{in} Antenna input current

ℓ_1 Length of longest part of dipole from feed point to the end

ℓ_2 Length of shortest part of dipole from feed point to the end

n Number of quarter wavelengths long

N Number of dipoles

P_r Radiated power

r Antenna series resistance per unit length

R Range from center of antenna in meters

R_{in} Antenna input resistance

r_m Mutual resistance

r_s Antenna self resistance

s Distance between dipoles

v Wave velocity along antenna

V_{max} Maximum antenna voltage

Z_o Characteristic impedance

α Attenuation constant

δ Skin depth (meters)

ϵ_o Free-space dielectric constant (8.85×10^{-12})

η Antenna radiation efficiency compared with that of a perfect monopole

λ Free-space wavelength

ω $2\pi f$

σ Earth conductivity (mho/meter)

ϕ Angle in azimuthal plane measured from antenna axis

ϑ Angle in elevation plane measured from antenna axis

INTRODUCTION

A program of very low frequency antenna research and development has been in progress at the Naval Weapons Center Corona Laboratories for the past five years. It has been found that the horizontal VLF transmitting antenna, requiring no ground plane, is much easier to construct and is less expensive than the vertical monopole antenna that is typical of the most modern VLF transmitting antennas in use at the present time. In addition, the horizontal antenna operates more efficiently over low conductivity material, of which much of the earth is composed. Its bandwidth, which is 100 times greater than that of the equivalent vertical antenna, increases both the rate of transmission and the stability of the transmitted signal. The power radiating capability of the horizontal antenna is several hundred times greater than that of the vertical monopoles presently in use. Because VLF radiation propagates over the earth with less loss in an easterly direction than in a westerly direction, the omnidirectional radiation from a vertical monopole does not give omnidirectional coverage at a given radius from the transmitter. By contrast, the off-center-fed horizontal antenna naturally beams the VLF energy with more intensity in one direction than in the opposite direction. If the main antenna beam is pointed west, it can be designed to radiate equal signals at a given range in both directions. The radiation efficiency of a single dipole is only a few percent, but the efficiency can be multiplied to a high radiation efficiency by using closely spaced parallel dipoles. The extent to which the efficiency can be increased by this method is limited by the mutual resistance between dipoles. This limitation is examined and the results reported in this report. A large number of dipoles also limits the azimuthal beamwidth by the array factor. The beamwidth of the horizontal dipole can be increased for long dipoles by increasing the wave velocity along the antenna. However, if the wave velocity is too much greater than free space wave velocity, the elevation launch angle is high. This is the angle of maximum radiation in the elevation plane, and it should be as small as possible for long range propagation. One of the desirable features of the horizontal antenna is that the radiation in the elevation plane is launched at low angles, thus minimizing wasteful vertical angle radiation.

RADIATION PATTERNS

Equations have been derived to describe the performance of several types of horizontal antennas. The radiation patterns of the horizontal conductor near the earth are dependent upon the feed point position along the conductor and the method of termination at the conductor ends. The fields radiated from uniform current on an incremental length conductor have been derived by Wait (Ref. 1), Banos and Wesley (Ref. 2), Golden, et al. (Ref. 3), Moore and Blair (Ref. 4), and Biggs (Ref. 5). The radiated electric field in the elevation plane through the axis of the conductor is

$$E_\theta = j \frac{120\pi}{R\lambda} (I \, d\ell) \frac{U \sin\theta}{U + \sin\theta} \tag{1}$$

and in the azimuthal plane the field is vertically polarized and is

$$E_Z = j \frac{120\pi}{R\lambda} (I \, d\ell) \, U \cos\phi \tag{2}$$

where

$$U = \sqrt{\frac{\omega\epsilon_o}{j\sigma}} = \sqrt{\frac{f \times 10^{-9}}{j \, 18\sigma}}$$

If these fields are equated to the fields radiated by a perfect lossless vertical monopole, $E_Z = (\sqrt{90P_r})/R$, an equation for the power radiated by the horizontal incremental conductor results. When this equation is divided by the input power at the antenna terminals, the radiation efficiency is

$$\eta_Z = \frac{160\pi^2 \omega\epsilon_o}{\sigma R_{in}} \cos^2\phi \left(\frac{I \, d\ell}{\lambda I_{in}}\right)^2 \tag{3}$$

The radiation patterns for particular antenna configurations can now be derived by summing up the current on the differential lengths by integrating the current distribution on that type of antenna.

Z_c-TERMINATED ANTENNA

If a very large bandwidth is needed, the dipole is terminated at each end with its characteristic impedance and fed at any position along its length. The resulting radiated power pattern in terms of efficiency, for the azimuthal plane, is

$$\eta_Z = \frac{\frac{4}{3}\pi^2 fC_p \cos^2\phi}{\sigma \frac{c}{v}} \left[\frac{1 - e^{-\alpha\lambda \ell_{1\lambda} - j2\pi \ell_{1\lambda}\left(\frac{c}{v} - \cos\phi\right)}}{\alpha\lambda + j2\pi\left(\frac{c}{v} - \cos\phi\right)} + \frac{1 - e^{-\alpha\lambda \ell_{2\lambda} - j2\pi \ell_{2\lambda}\left(\frac{c}{v} + \cos\phi\right)}}{\alpha\lambda + j2\pi\left(\frac{c}{v} + \cos\phi\right)} \right]^2 \tag{4}$$

If this antenna is fed at one end against a zero impedance ground plane, it is a Beverage wave antenna. The second term within the brackets is zero and the term outside the brackets is doubled because the input resistance is halved, and

$$\eta_Z = \frac{\frac{8}{3}\pi^2 fC_p \cos^2\phi}{\sigma \frac{c}{v}} \left[\frac{1 - e^{-\alpha\lambda \ell_{1\lambda} - j2\pi \ell_{1\lambda}\left(\frac{c}{v} - \cos\phi\right)}}{\alpha\lambda + j2\pi\left(\frac{c}{v} - \cos\phi\right)} \right]^2 \tag{5}$$

The power radiation patterns in the elevation plane can be derived by simply replacing the $\cos^2\phi$ term outside the brackets of Eq. 4 and 5 with $[\sin\theta/(U + \sin\theta)]^2$ and ϕ inside the brackets with θ. This can be seen by comparing Eq. 1 and 2.

OPEN-TERMINATED DIPOLE

The horizontal dipole near the earth is most efficient when placed over low conductivity earth. In areas of low conductivity, it is usually very difficult to construct terminating ground planes. So in most instances an open-terminated dipole must be used. This type of antenna is more narrow band (50% to 100% half power bandwidth) than the Z_o-terminated antenna, but it radiates with greater efficiency.

The power radiation pattern is found in the same manner as described above by integrating over the current distribution. This has been done in a previous report (Ref. 6), and for a resonant dipole fed at a current maximum the power radiation pattern in terms of the radiation efficiency in the azimuthal plane is

$$\eta_Z = \frac{\frac{8}{3}\pi^2 f C_p \cos^2\phi}{\sigma \frac{c}{v}\left(\tanh \alpha\lambda \ell_{1\lambda} + \tanh \alpha\lambda \ell_{2\lambda}\right)} \left\{ \frac{\sinh \alpha\lambda \ell_{1\lambda} + j^n \cos\left(2\pi \ell_{1\lambda} \cos\phi\right)}{\left[\alpha\lambda + j2\pi\left(\frac{c}{v} - \cos\phi\right)\right]\cosh \alpha\lambda \ell_{1\lambda}} + \frac{\sinh \alpha\lambda \ell_{2\lambda} + j^n \cos\left(2\pi \ell_{2\lambda} \cos\phi\right)}{\left[\alpha\lambda + j2\pi\left(\frac{c}{v} + \cos\phi\right)\right]\cosh \alpha\lambda \ell_{2\lambda}} \right\}^2 \tag{6}$$

Here again the elevation pattern is derived by replacing the $\cos^2\phi$ term outside the brackets with $[\sin\theta/(U + \sin\theta)]^2$, and replacing ϕ inside the brackets with θ. The efficiencies computed by Eq. 4, 5, and 6 are the efficiencies of the horizontal antenna compared to a perfect lossless vertical antenna.

END-LOADED DIPOLE

If only limited space is available, the most efficient short dipole (dipole length $< \lambda/2$) is the end-loaded dipole. The end loading can consist of several conductors laid out in a radial manner at the ends of the dipole and sufficiently long to make the dipole resonant.

The power radiation pattern is found by integrating over the truncated cosine current distribution and has been derived in a previous report (Ref. 7). It is

$$\eta_Z = \frac{8.77 \times 10^{-8} f \ell_\lambda^2}{\sigma R_{in}} \left(\frac{\sin \pi \frac{c}{v} \ell_\lambda}{\pi \frac{c}{v} \ell_\lambda}\right)^2 e^{-\alpha\lambda(\ell_\lambda/2)} \cos^2\phi \tag{7}$$

This is the radiation efficiency in the azimuthal plane. A short dipole will have nearly a uniform current distribution, which gives a four-fold increase in efficiency over the triangular current distribution of a short open-terminated dipole. To obtain the power pattern in the elevation plane, $\cos \phi$ is replaced by $\sin \theta/(U + \sin \theta)$ in Eq. 7.

EFFECT OF FAST WAVE VELOCITY ON HORIZONTAL ANTENNA EFFICIENCY AND RADIATION PATTERN

The wave velocity along a conductor near the earth is usually much less than its velocity in free space; c/v is typically about 1.4 for a conductor about one meter above the earth. Both the wave antenna and the resonant dipole have very low radiation efficiency at this slow wave velocity, as is shown by Fig. 1 and 2. The wave velocity can be increased by inserting series capacitors into the antenna, which in effect cancels a portion of the antenna inductance. This increases the radiation efficiency as shown in Fig. 1 and 2. The optimum wave velocity for efficiency is greater than free space wave velocity and occurs when c/v is about 0.9 for the sky wave radiation. The optimum wave velocity for the ground wave (see Fig. 2) is slower (c/v = 1.05). For long range propagation, the sky wave is more important than the ground wave. The wave velocity along the antenna has an effect not only upon radiation efficiency but also upon the beamwidth and elevation launch angle of the sky wave (see Fig. 3). The beam launch angle can be varied over a wide range of angles (see Fig. 4). This may be important at VLF for selecting the angle for the best excitation factor. The data in Fig. 4 is for a long, Z_0-terminated-wave antenna, but the resonant dipole data shows similar characteristics (see Fig. 5). Beam launch angles from 10° to 50° can be selected by using different values of c/v, but the lower launch angles are accompanied by lower radiation efficiency, as are the narrower beamwidths (see Fig. 3).

The faster wave velocities also broaden the beamwidth in the azimuthal plane, giving greater coverage over the earth's surface.

The resonant dipole sky wave radiates most efficiently when c/v = 0.9 (see Fig. 6). However, for a given length dipole there is not much difference in efficiency for c/v values from 0.8 to 1.0 (see Fig. 6). Therefore the beam launch angle can be varied considerably, without loss of efficiency, by changes in antenna wave velocity. The

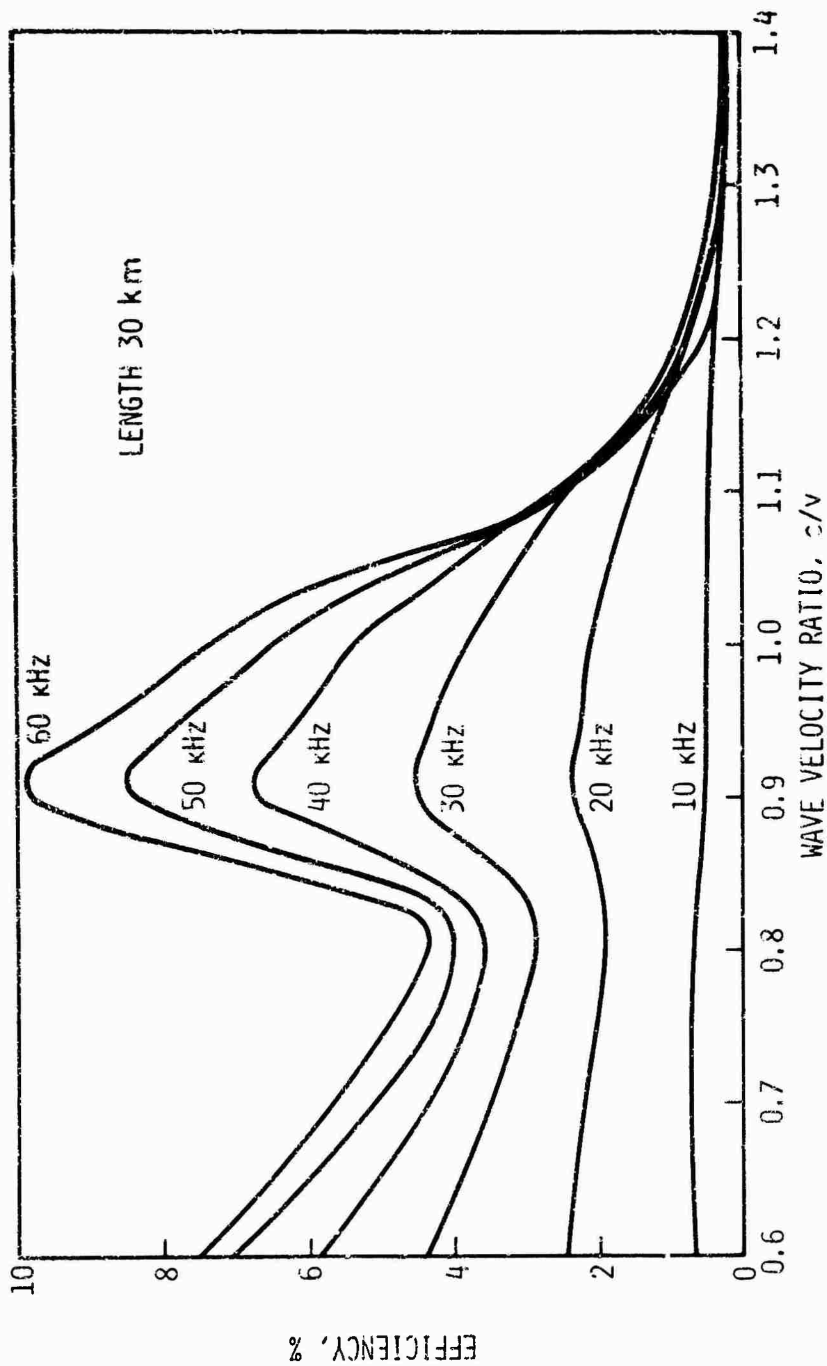

FIG. 1. Hawaiian Wave Antenna Radiation Efficiency in the Elevation Plane.

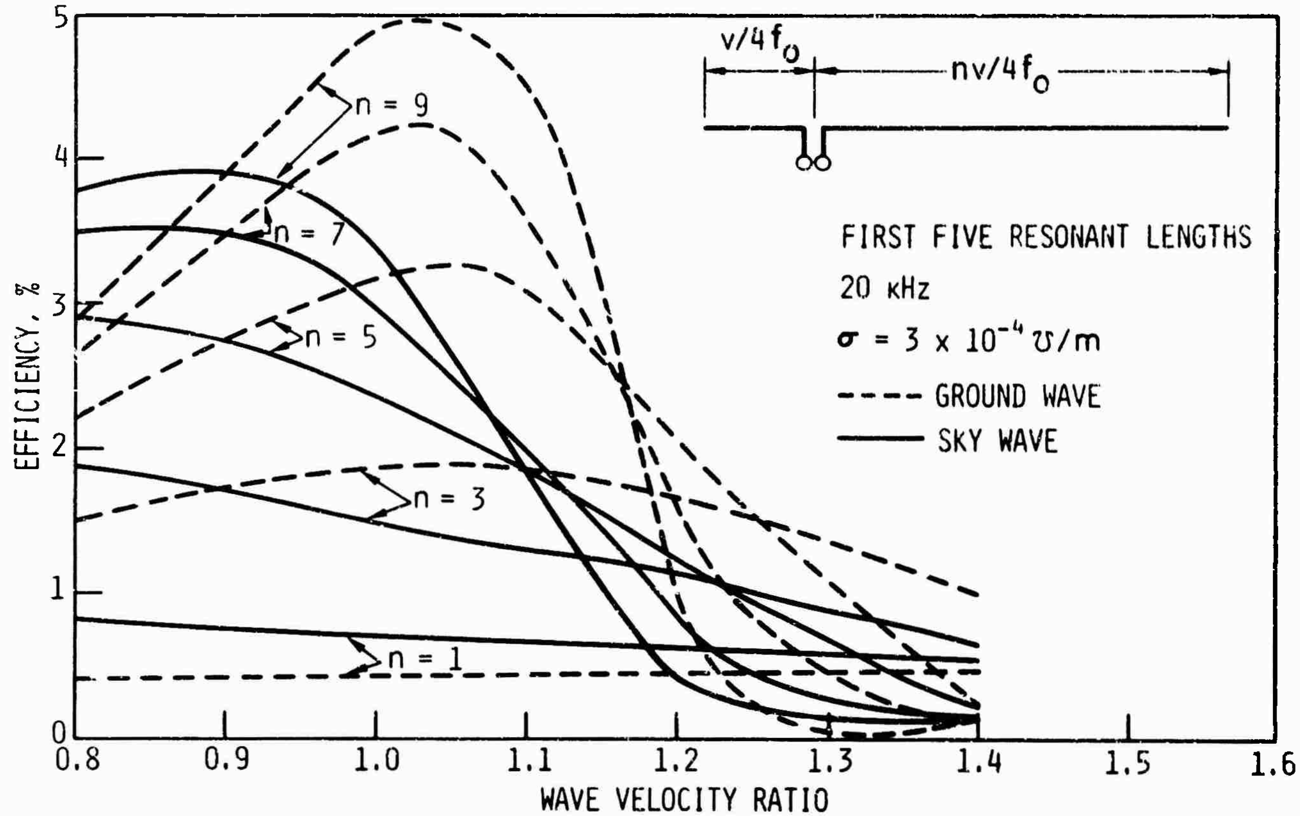

FIG. 2. Maximum Efficiency in Elevation and Azimuth Planes for a Dipole on Hawaiian Lava.

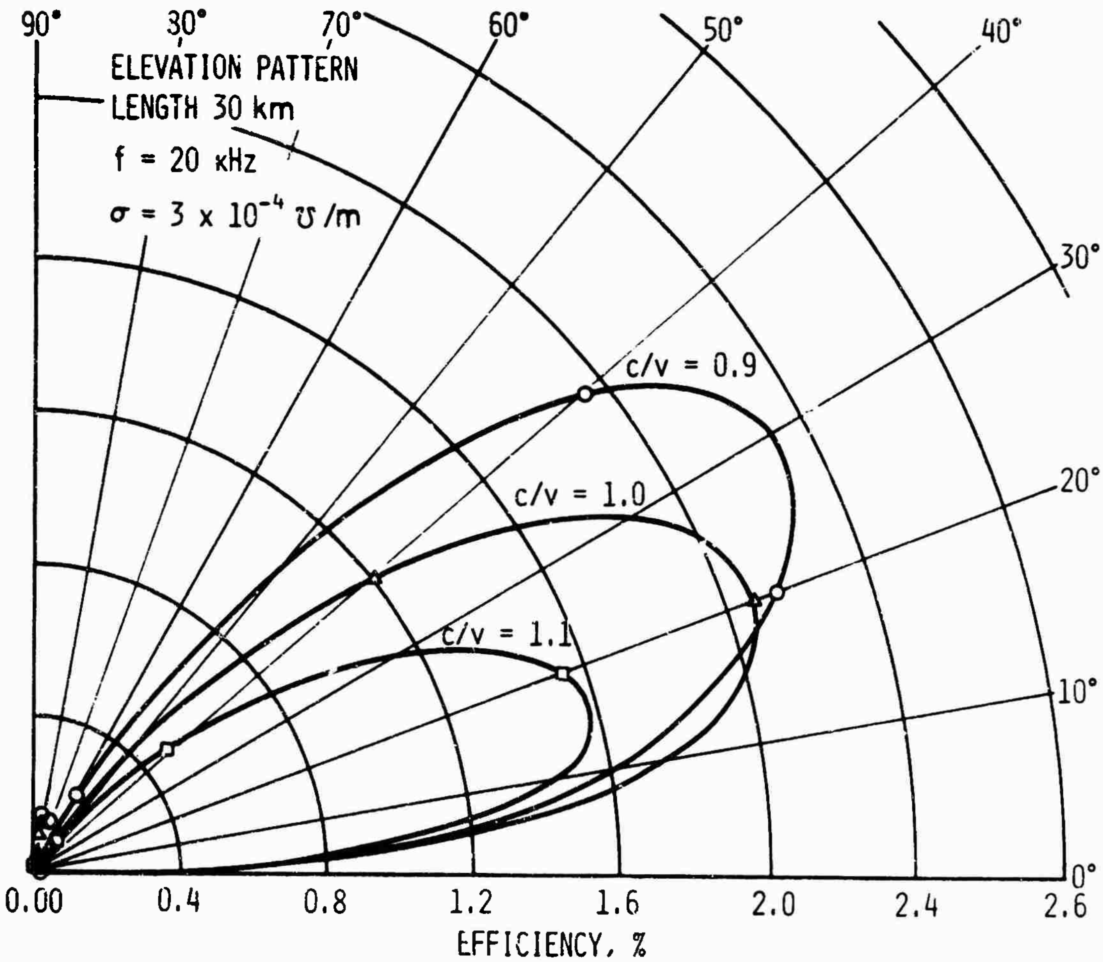

FIG. 3. Hawaiian Wave Antenna Radiation Efficiency.

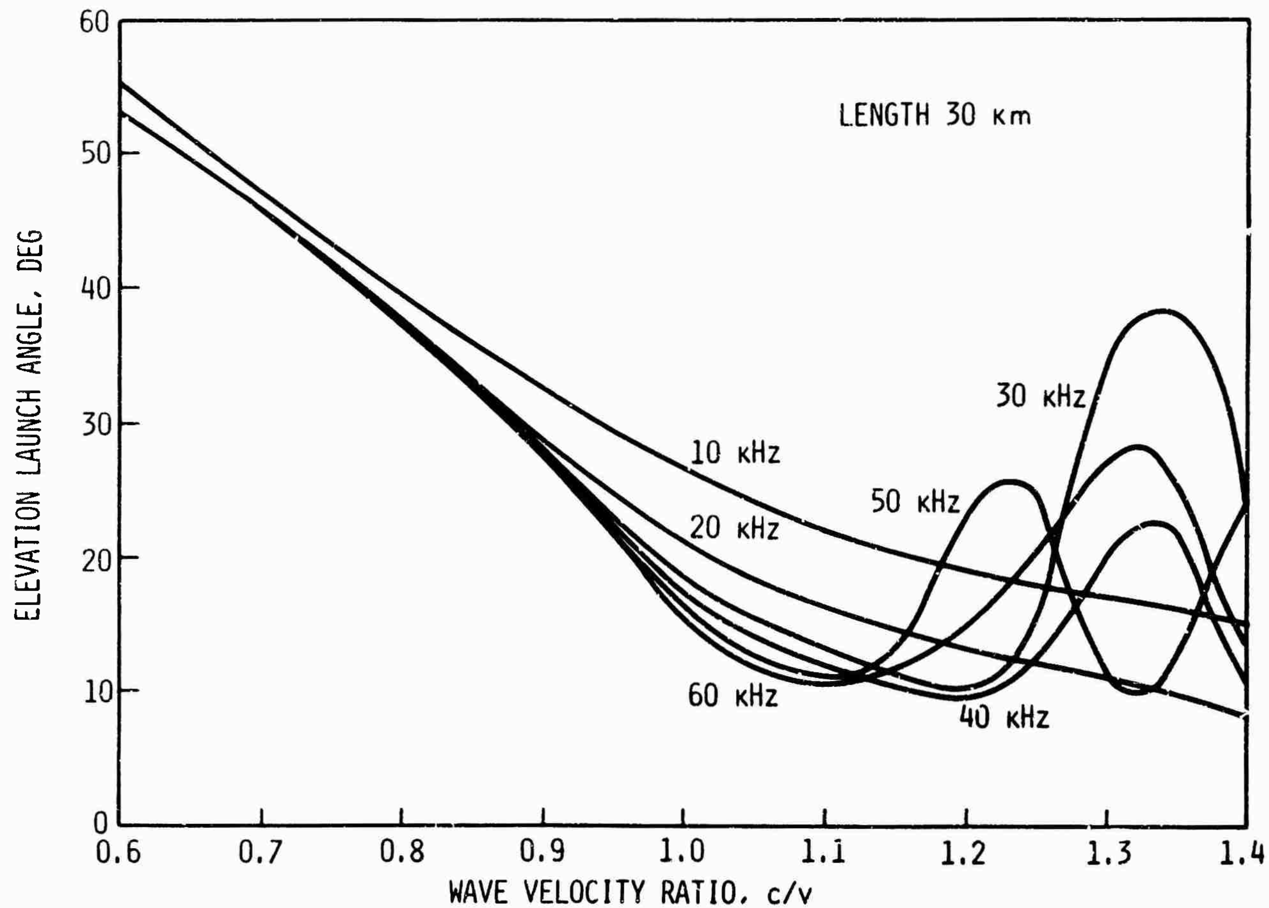

FIG. 4. Hawaiian Wave Antenna Launch Angle in the Elevation Plane Through Antenna Axis.

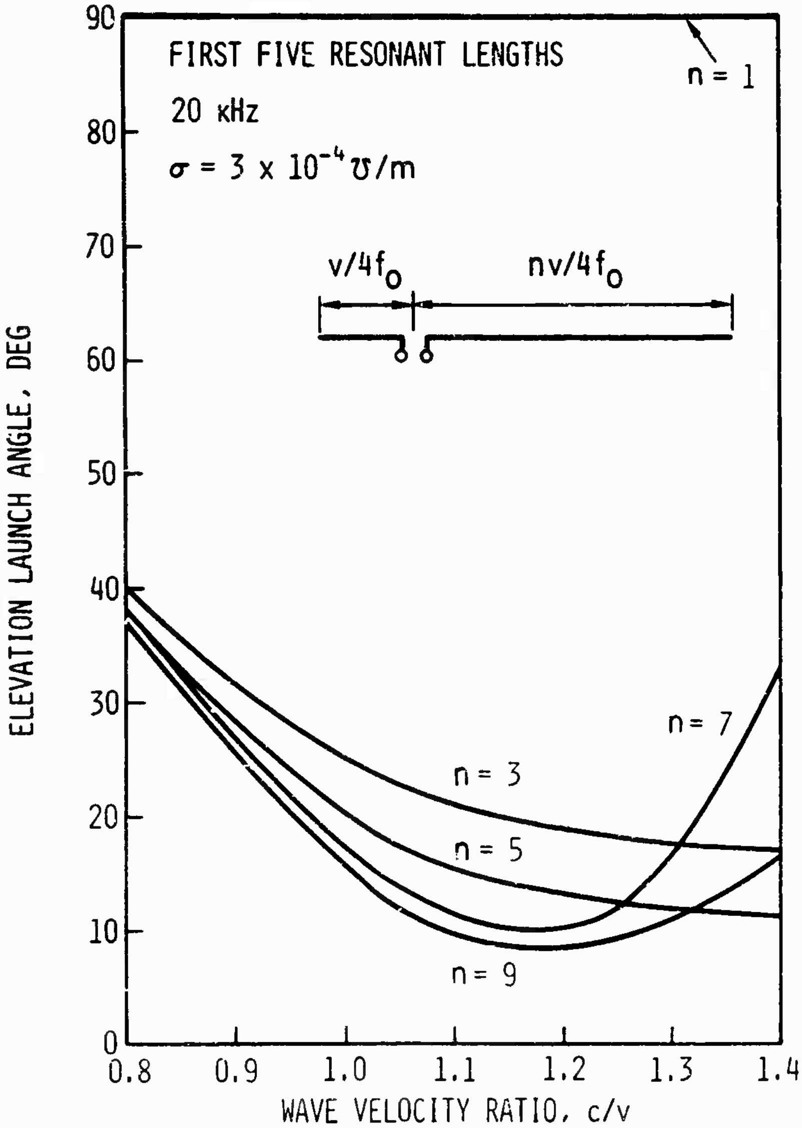

FIG. 5. Resonant Dipole Skywave Launch Angle.

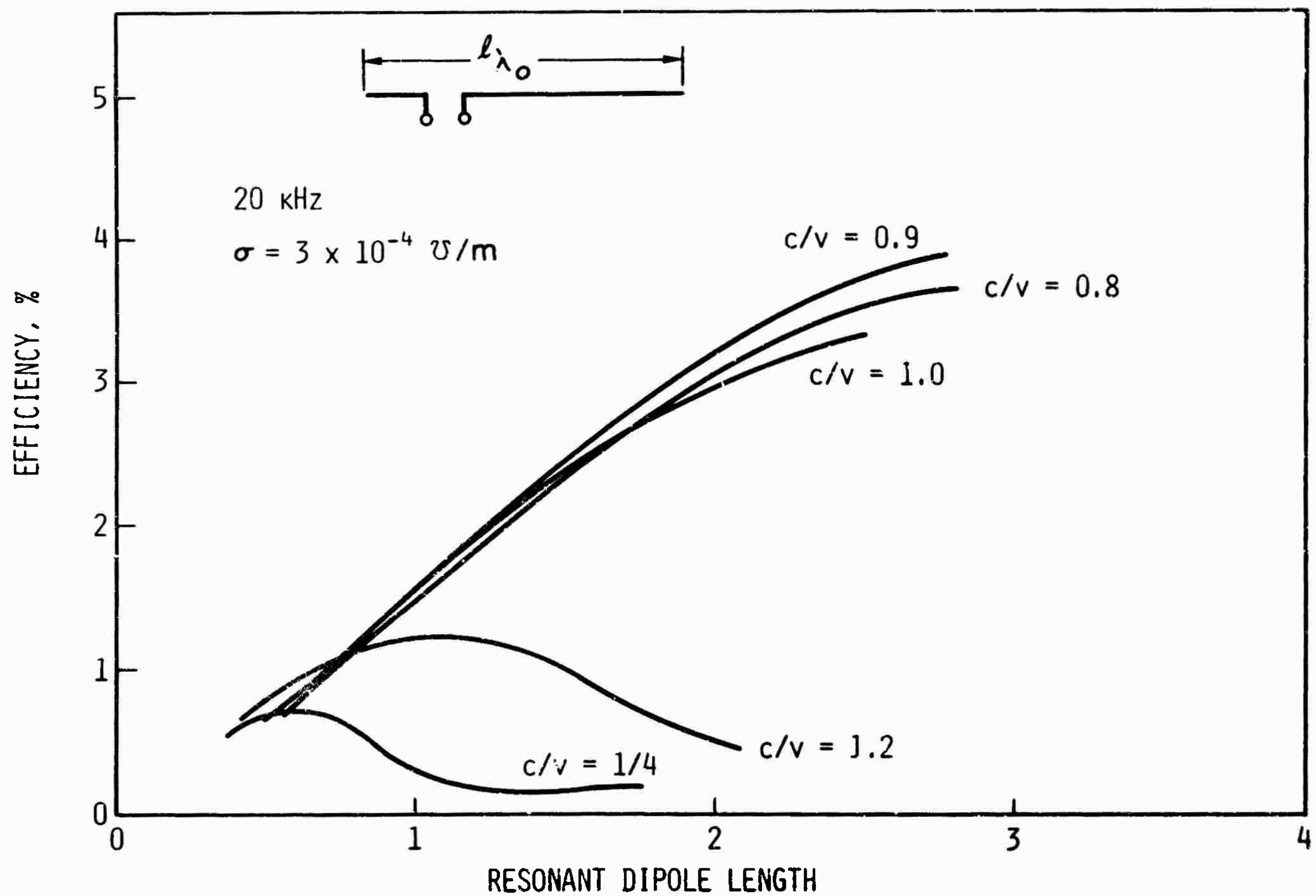

FIG. 6. Maximum Efficiency in Elevation Plane for a Dipole on Hawaiian Lava with Several Values of Wave Velocity.

efficiency appears to be nearly proportional to length for the range of wave velocities above, up to lengths of about 3 wavelengths. The data in Fig. 6 is for areas whose conductivity is the same as the Hawaiian lava beds (3×10^{-4} mho/meter at 20 kHz).

EFFECT OF PARALLELING DIPOLES ON THE ARRAY EFFICIENCY AND RADIATION PATTERNS

When N closely spaced parallel dipoles are connected in parallel and fed by a common transmitter, the radiation efficiency is increased N-fold, reduced by a deteriorating factor caused by mutual resistance induced in each dipole by all the other dipoles in the array (Ref. 8 and Ref. 7). It can be shown using Eq. 6 that the antenna losses have the greatest effect on efficiency when $c/v = 1.0$ and $\phi = 0°$. Under these conditions it can also be shown that the antenna efficiency is inversely proportional to the antenna attenuation factor, $\alpha\lambda$, if $\alpha\lambda < 1.0$, which is the case for any practical antenna. It can easily be shown that, under these restrictions,

$$\alpha\lambda = \frac{r\lambda}{2Z_o} \tag{8}$$

Therefore the radiation efficiency is inversely proportional to r, the total self and mutual resistance per unit length.

The input resonant resistance at a current maximum is

$$R_{in} = \frac{r\ell}{2} \tag{9}$$

The efficiency is therefore inversely proportional to the resonant input resistance. The efficiency gain of an array of dipoles over one dipole can be calculated by summing up the inverse of the ratios of the total resistance per unit length to the self resistance per unit length of each dipole:

$$\frac{\eta_{array}}{\eta_{one\ dipole}} = \sum_{N=1}^{N} \frac{1}{1 + \sum_{N=2}^{N} \frac{r_m}{r_s}} \tag{10}$$

The mutual resistance and self resistance of conductors near the earth has been derived by Carson (Ref. 9). The ratio of mutual resistance to self resistance, r_m/r_s, is plotted versus the separation between conductors in skin depths (see Fig. 7). Figure 7 is used with Eq. 10 to compute the efficiency gain of an array over one dipole with various spacing between dipoles (see Fig. 8). To avoid excessive loss in efficiency, resonant dipoles in an array should be spaced at least four skin depths apart.

Radiation efficiency measurements made on a 5-dipole array constructed on the lava beds of Hawaii tend to confirm the theoretical increase in efficiency (see Fig. 9 and 10). The dipoles were resonant at 10 kHz, where the ratio of mutual to self resistance was measured to be 0.1, which would indicate a dipole spacing of 3.6 skin depths (see Fig. 7). A five-dipole array with this spacing should have an efficiency gain of 4 over one dipole (see Fig. 8). The efficiency of the 5-dipole array is approximately 4 times that of the single dipole at 10 kHz. The efficiency gain of the array is larger at the higher frequencies, as it should be, because the skin depth decreases and s/δ becomes larger. The theoretical resonant array efficiency gain applies reasonably accurately to non-resonant dipoles as well.

The azimuth beamwidth of dipole arrays is narrowed over that of a single dipole by the array factor. The azimuth patterns of arrays of dipoles are obtained by multiplying the power pattern of a single dipole (Eq. 4, 5, 6, and 7) by the array factor of an array of isotropic radiators. This array factor, which was derived by Kraus (Ref. 10), is

$$F = \left[\frac{\sin\left(N\frac{\pi s}{\lambda}\sin\phi\right)}{N\sin\left(\frac{\pi s}{\lambda}\sin\phi\right)}\right]^2 \qquad (11)$$

The radiation patterns of arrays of dipoles, whose single dipole patterns are described by Eq. 4, 5, 6, and 7, are found by multiplying these equations by Eq. 11.

An antenna has been designed to transmit from the lava beds of Hawaii to illustrate the radiation efficiency, power radiating capability, and broad bandwidth that can be achieved with resonant fast wave dipoles. This area was chosen because the electrical parameters needed to compute the radiation pattern (see Eq. 6) have been measured on experimental horizontal antennas above these lava beds. The 18 dipoles are

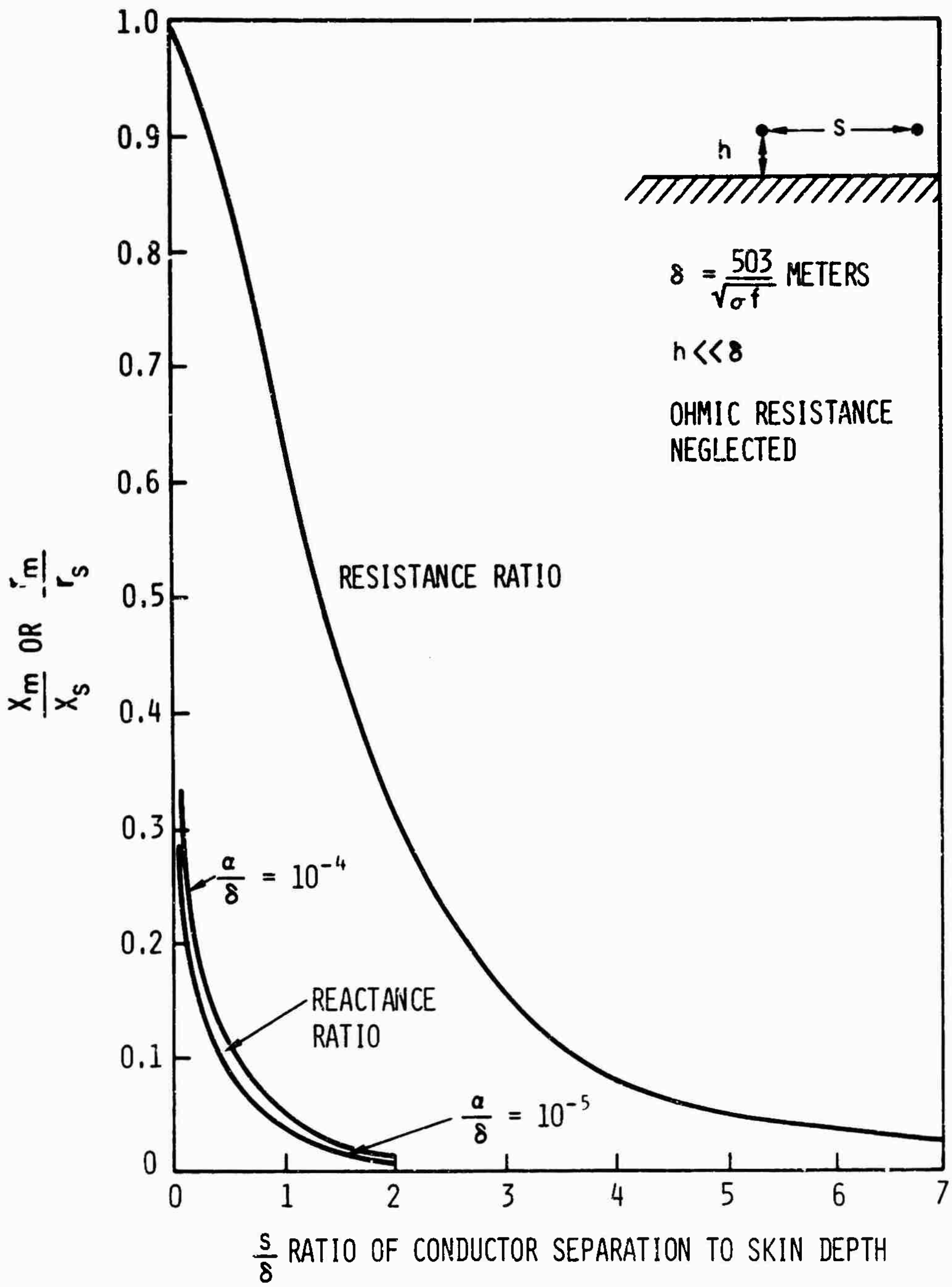

FIG. 7. Ratio of Mutual Impedance to Self Impedance for Two Parallel Conductors Near Earth.

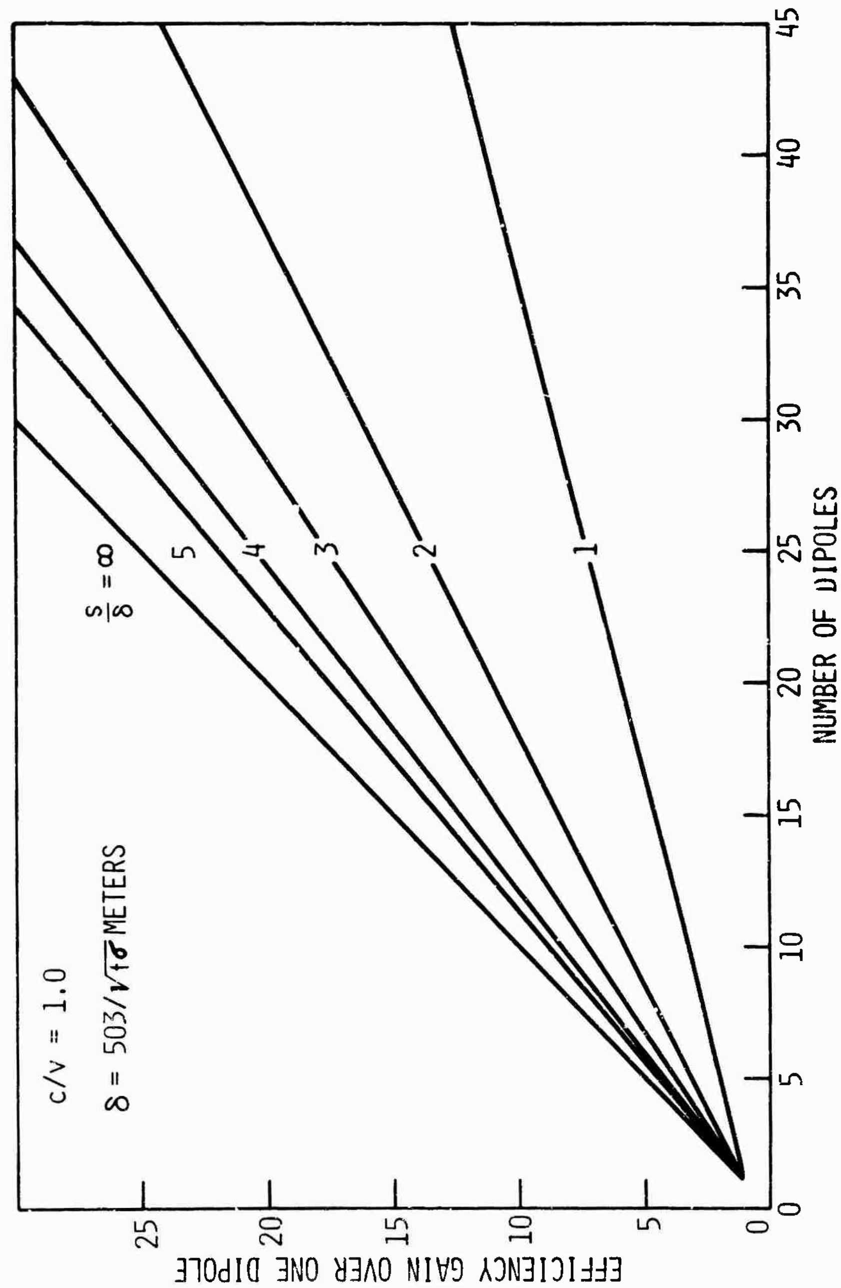

FIG. 8. Array of Resonant Parallel Equally Spaced Dipoles.

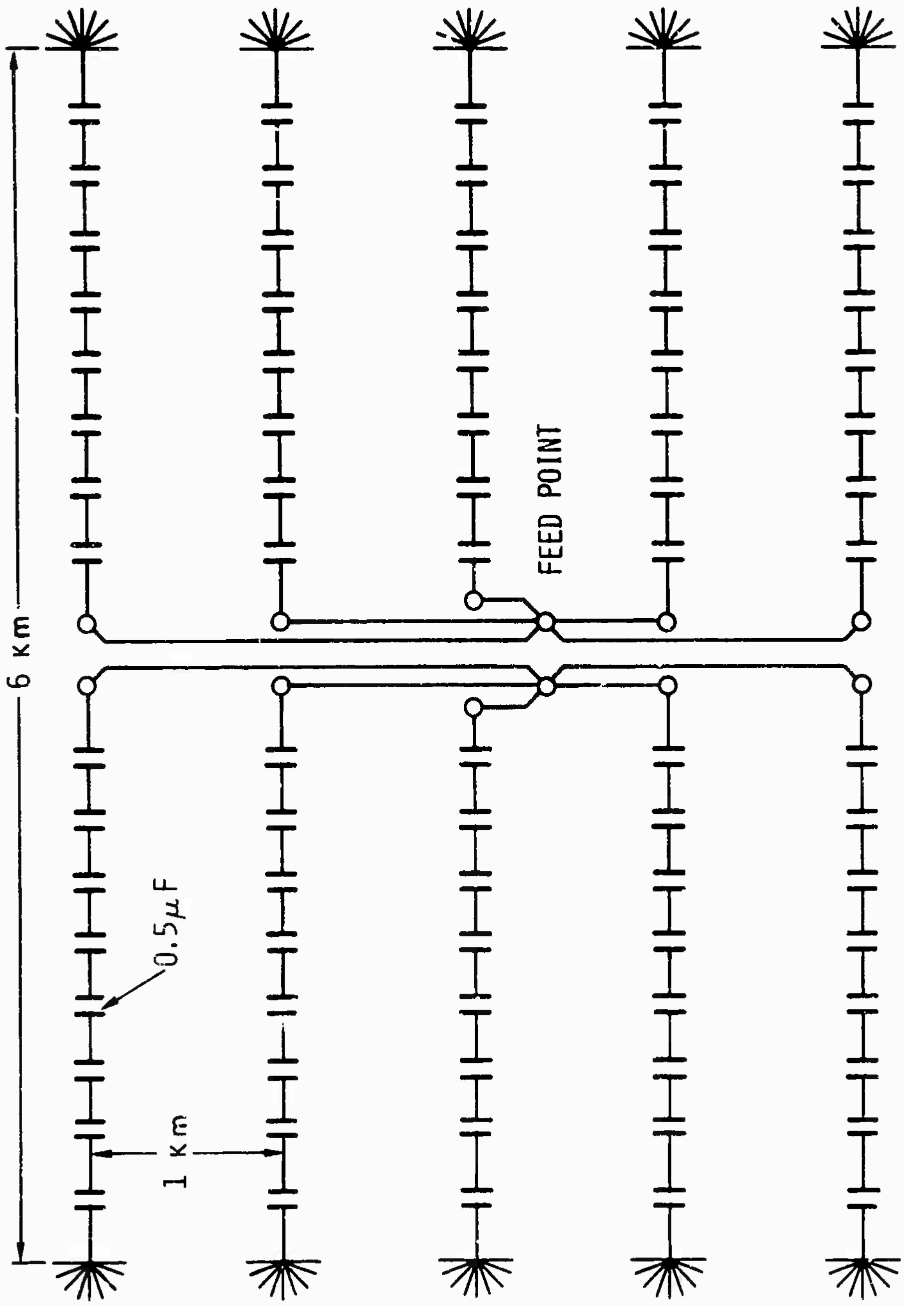

FIG. 9. VLF Transmitting Antenna Constructed Over Hawaiian Lava Beds.

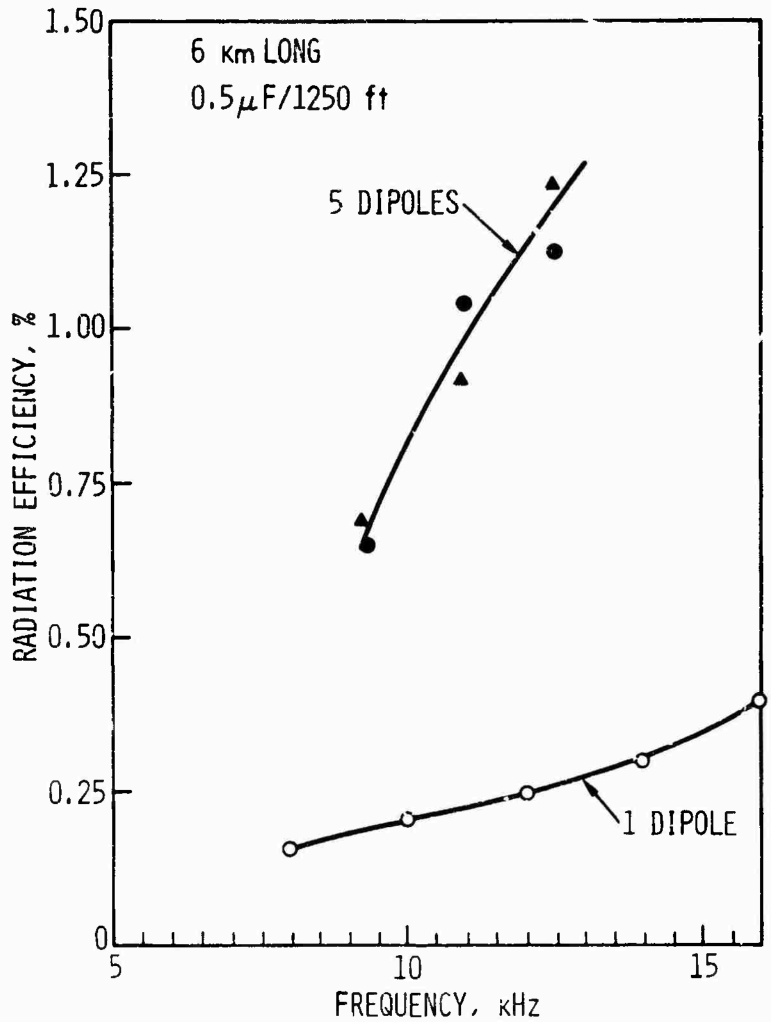

FIG. 10. End-Loaded Dipole Array on Hawaiian Lava.

one and a half wave resonant at the middle of the VLF band (20 kHz) and fed quarter wave from one end with the resulting power radiation pattern shown in Fig. 11. The effects of the array factor and of mutual resistance between dipoles have been taken into consideration in computing this radiation pattern.

The power radiating capability of this antenna far exceeds the power output of any existing transmitter. The limiting parameter is the maximum antenna voltage before the onset of corona. The onset of corona at VLF occurs at about 35 kV for a #6 wire, 20 ft above the ground (Ref. 11). The maximum power radiated can be computed from transmission line theory and is

$$P_{r\,max} = \frac{N\left(V_{max} \cosh \frac{\alpha\lambda}{4}\right)^2 \eta \left(\tanh \frac{\alpha\lambda}{4} + \tanh \frac{5\alpha\lambda}{4}\right)}{Z_o} \quad (12)$$

where η is the efficiency of the dipole array and V_{max} is the maximum voltage on any dipole. Using the corona onset voltage (35 kV) as the maximum dipole voltage, the maximum power radiated by the array is 22 MW. This would require 54 MW of transmitter power. A more modest goal of matching the radiated power radiated from the most powerful VLF vertical antenna, 1.5 MW, would require a maximum antenna voltage of 9 kV on the horizontal dipole array.

EFFECTS OF NON-RECIPROCAL VLF PROPAGATION ON RADIATION PATTERN

As noted previously, VLF radiation propagates around the earth with less attenuation in an easterly direction than in a westerly direction. Therefore, to obtain omnidirectional coverage on the earth, the transmitting antenna must beam the VLF in a westerly direction. The horizontal dipole has this type of radiation pattern, while the vertical monopole radiates equally in all directions.

This non-reciprocity propagation has been shown theoretically to be proportional to the component of the earth's magnetic field that is horizontal and transverse to the direction of propagation (Ref. 12). There is no difference in the propagation attenuation in a northerly or southerly direction. The ratio of attenuation rate off the northerly magnetic path to the rate on the south-north path varies as the sine of

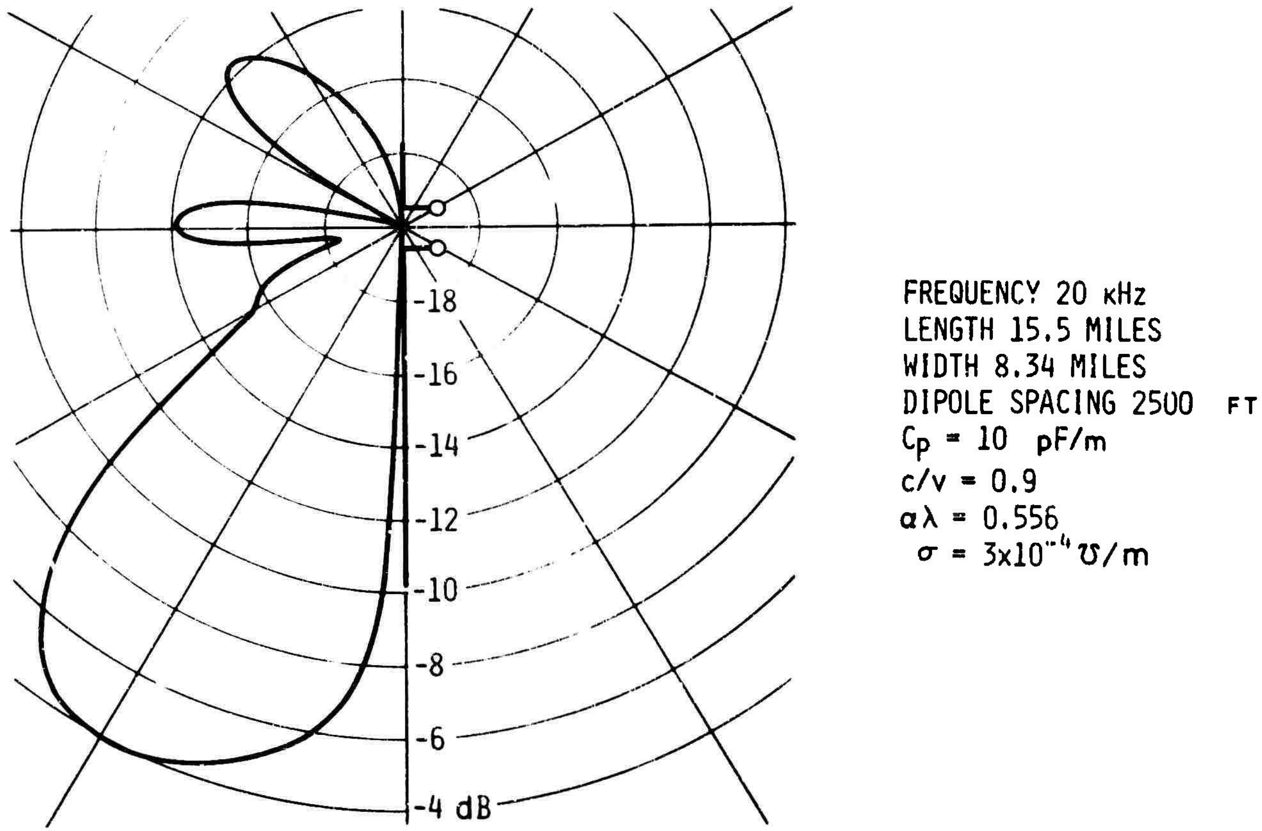

FIG. 11. Efficiency in Elevation Plane of Array of 18 Dipoles on Hawaiian Lava.

the azimuth angle off the northerly path. Experimental evidence (Ref. 13 and 14) shows that the increase in attenuation rate of westerly sea water path over an easterly sea water path varies from 0.5 dB per megameter at 25 kHz to 2.3 dB per megameter at 10 kHz (see Fig. 13). Since the attenuation rate increase is greater at lower VLF, the directivity of the antenna radiation pattern must be greater for the lower frequencies and more directive for larger ranges over which omnidirectional coverage is desired.

The required antenna radiation patterns for omnidirectional coverage at a range of 10 megameters from the transmitter over a sea water path are shown in Fig. 14. The greatest directivity is needed at 10 kHz, where the required half power beamwidth is 70° and the radiation in the magnetic westerly direction must be 23 dB greater than that in the magnetic easterly direction. At 15 and 20 kHz, less directivity is required for omnidirectional coverage. However, at 20 kHz a half power beamwidth of 120° and a west over east radiation ratio of 8 dB are needed.

It is evident from comparing the radiation patterns of the 18-dipole arrays (Fig. 11 and 12) with the required radiation pattern at 20 kHz (Fig. 14) that the array will not give omnidirectional coverage. There is a deficiency of radiation in the northerly and southerly directions. This could be provided by a smaller center-fed array of resonant dipoles perpendicular to the 18-dipole array.

ENVIRONMENTAL EFFECTS ON EXPERIMENTAL ARRAY

The radiated field phase stability of VLF antennas is important in navigation systems. The field phase shift due to rain on the horizontal dipole might be expected to be great due to its proximity to the earth. However, field measurements made on the 5-dipole array in Hawaii before and during a rain storm indicated only a small phase shift (see Fig. 15). This was no doubt due to large antenna bandwidth. Rubidium frequency standards were used to control the transmitter and receiver. The radiated field was measured 26 km off the end of the antenna, where the skywave was gated out and only the ground wave was received.

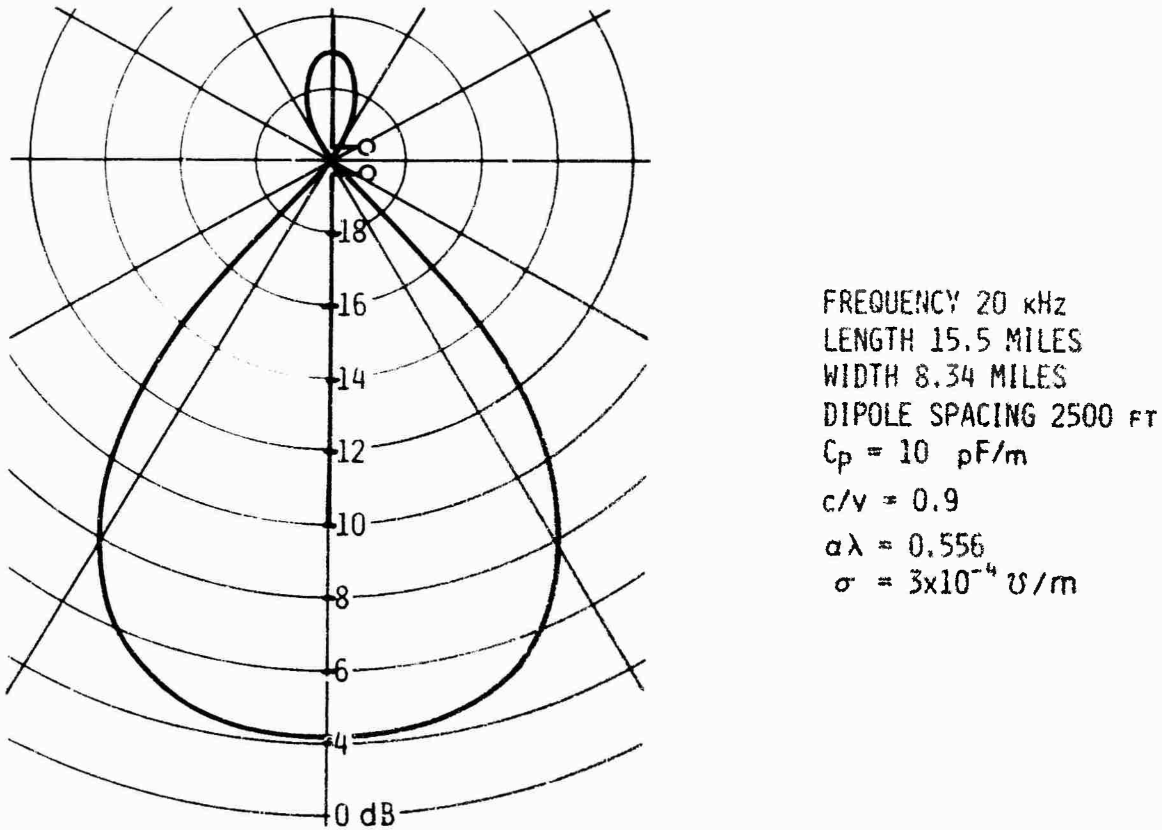

FIG. 12. Efficiency in Horizontal Plane of Array of 18 Dipoles on Hawaiian Lava.

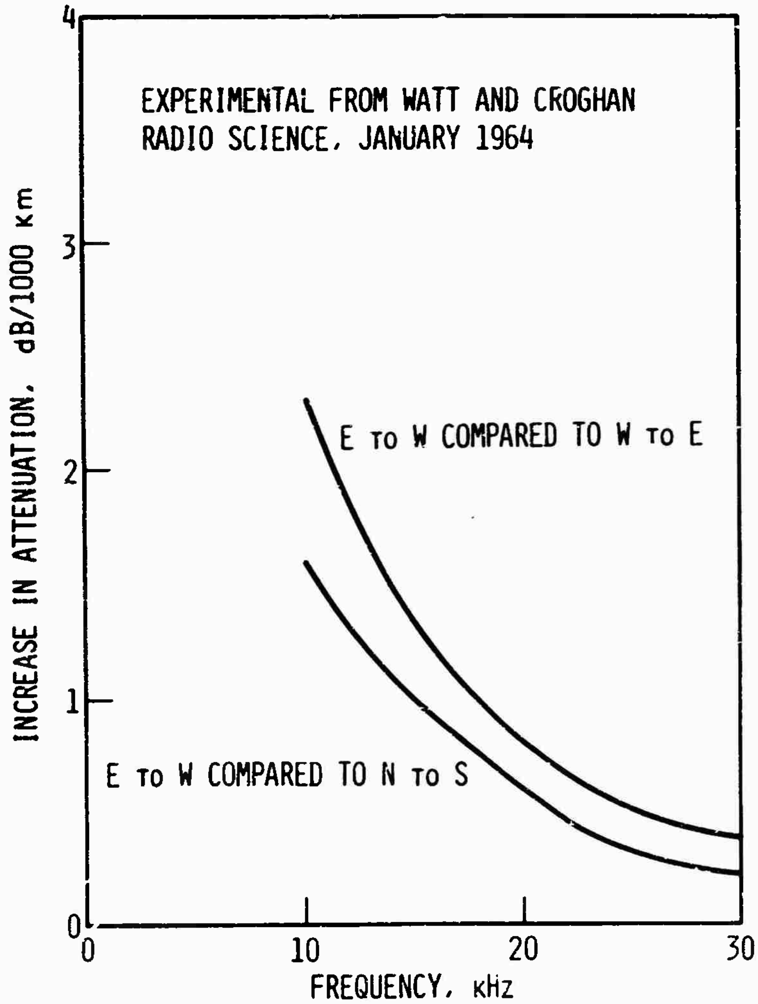

FIG. 13. Differences in VLF Attenuation Rate Over Reciprocal Sea Water Paths.

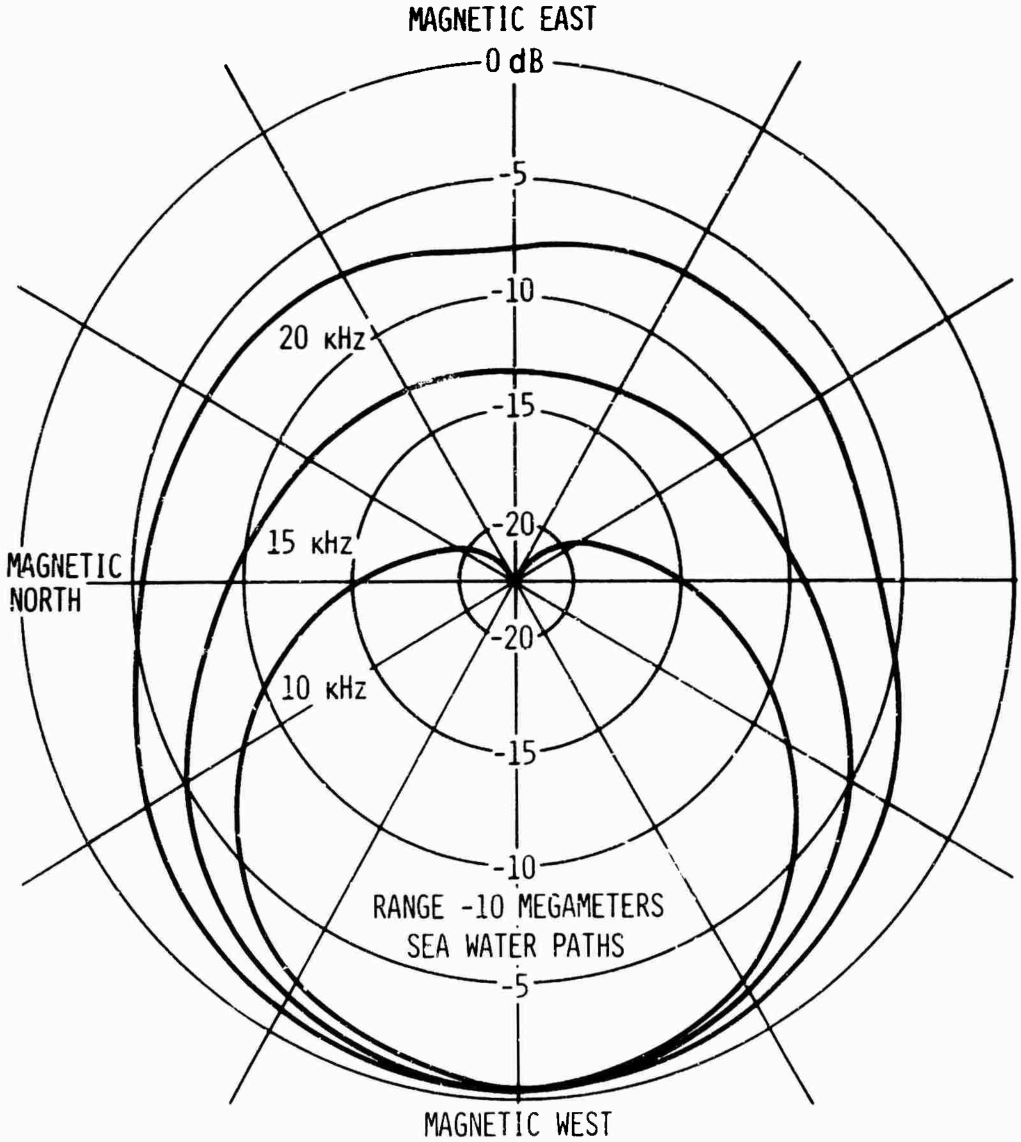

FIG. 14. Antenna Radiation Patterns Required for Omnidirectional Coverage.

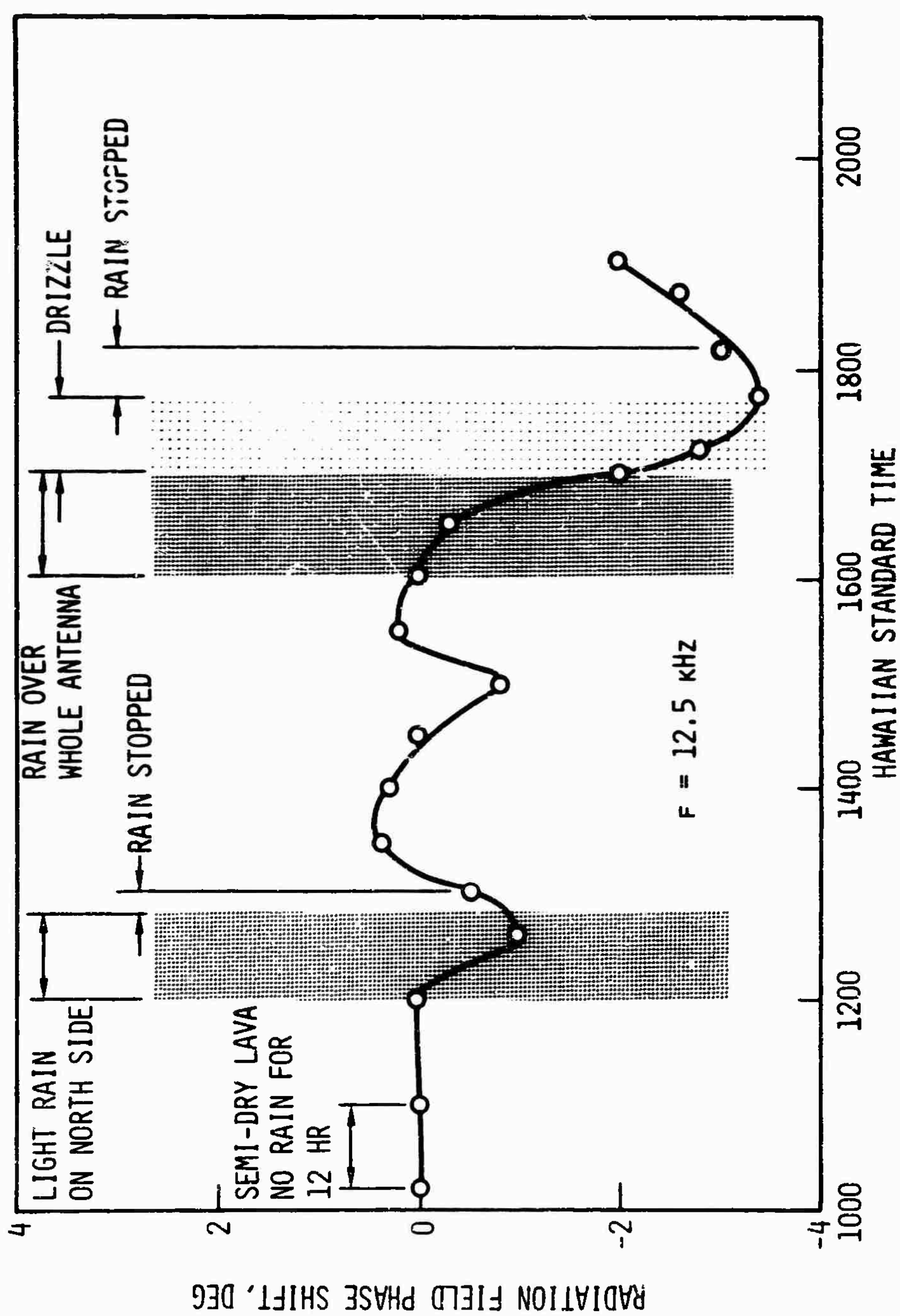

FIG. 15. Effect of Rain on Phase Stability of End-Loaded Five-Dipole Array (Radiated Field Measured 26 km Off the End of the Antenna).

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13. ABSTRACT

Horizontal VLF transmitting dipole arrays are much easier and less expensive to construct than vertical VLF transmitting antennas in use at the present time. The horizontal dipoles have much greater power-radiating capability and bandwidth. The theoretical and experimental effects of mutual resistance on array efficiency gain over one dipole are presented. The radiation efficiency is greatly increased by increasing the wave velocity along the resonant dipole. Radiation characteristics of a theoretical 18-dipole array on Hawaiian lava are shown. The antenna radiation pattern needed at VLF in order to get omnidirectional coverage is presented. Directivity is needed due to the non-reciprocal east-west propagation attenuation.

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